

The Miniaturized Autonomous Moored Profiler (Mini AMP)

Andrew Barnard
WET Labs, Inc
620 Applegate St., P. O. Box 518, Philomath, OR 97370
phone: (541) 929-5650 fax: (541) 929-5277 email: andrew@wetlabs.com

Contract Number: N0001405C0075
<http://www.wetlabs.com/Research/barnard/miniampabstract.htm>

LONG-TERM GOALS

High resolution, 4-D environmental characterizations of the physical and bio-optical structure of the near shore and coastal oceans are needed in order significantly improve our understanding of the complex biogeochemical processes acting these regions. Accurate assessments of the vertical structure of the physical, optical, and biogeochemical properties in the coastal environment are also vital to many naval operations (i.e. MCM, ASW). Furthermore, the development of a national backbone of observing systems envisioned for the US coastal regions requires reliable, affordable, autonomous monitoring stations to provide early warning indicators of events and trends. As such, there is a definite need for the development of intelligent, reliable, high resolution, moored profiling systems. The long-term goal of this project is to develop a compact, low power, autonomous, scalable, bottom-up profiling system, termed the Miniaturized Autonomous Moored Profiler (AMP), to support a variety of long-term coastal applications, where real-time, high vertical resolution physical and bio-optical data are required. The focus of this development effort is to provide a system that offers the user a high level of flexibility in sensing parameters, data telemetry and data control, while maintaining a high level of performance, reliability, accuracy, and ease of use.

OBJECTIVES

The primary goal of our Mini AMP Phase II efforts was to implement and validate two profilers. The primary embodiment of the AMP profiler includes an onboard winch system, a platform controller, a suite of sensing systems (CTD and optical sensors), a power system (power management and battery pack), and a telemetry system. Several AMP systems have been constructed and have undergone extensive field use by WET Labs engineers, scientists and researchers within the community. Field deployments conducted in conjunction with several research groups were a key requirement in demonstrating to the research community that the platform is operational and to ensure the viability of the end product. This testing was coordinated with ongoing naval efforts and other science research community activities. This process of testing and refinement is an ongoing effort, and has lead to a transition stage for the AMP systems into a viable commercial product.

APPROACH

The approach taken in the development of the AMP system was to: 1) construct an alpha AMP prototype, 2) test the alpha AMP prototype, 3) conduct a design review of alpha AMP, 4) construct and implement beta AMP prototypes, 5) develop a remote host interface software, and 6) conduct extensive beta AMP prototype operational testing. A team of engineers at WET Labs has been

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 2006		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE The Miniaturized Autonomous Moored Profiler (Mini AMP)				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) WET Labs, Inc. 620 Applegate Street, P.O. Box 518, Philomath, OR 97370				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 14	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

dedicated to the development of the AMP systems. Over 6 engineers and research scientists have been involved in the development, with each being tasked with the design of specific components. Dr. Percy Donaghay and Dr. James Sullivan of the University of Rhode Island, serving as consultants on this project, have played an invaluable role in the development, offering their profiling expertise in design and testing of the AMP. Both Drs. Donaghay and Sullivan had key roles in the initial implementation testing of the AMP prototypes and are leveraging their existing efforts utilizing the ORCAS profilers in the ONR LOCO project in the development of the AMP.

Our work over the past 2 years has culminated in the construction of 2 versions of the AMP profiler, one targeted for inshore and near-coastal environments (< 50 m) configured with instrumentation designed for monitoring water quality (termed AMP-WQ50), and one for coastal regions (< 100 m) capabilities of including a broader environmental sensing suite (termed AMP-ES100). To date, we have constructed a total of 4 AMP systems (2 AMP-WQ50 and 2 AMP-ES100), two of which were purchased by and have been delivered to other federal agencies (NOAA Chesapeake Bay Office and the Naval Undersea Warfare Center, Newport, RI division). The other 2 profilers are deliverables under this SBIR contract, and which have recently been used in other externally sponsored research programs (Rhode Island Coastal Alliance ORCASNET, and ONR OASIS).

WORK COMPLETED

The WET Labs, Inc Autonomous Moored Profiler (AMP) is a submersible vertically profiling platform for use in marine to freshwater water bodies (figure 1). The purpose of the platform is to sample the water column distributions of physical, biological, chemical and optical properties at a fixed geographical location over extended periods of time. The system provides sub-meter scale vertical resolution of these properties from the sea floor to the surface of the air-water interface. The AMP design includes a modular, self-contained, winch-driven profiling platform with an integrated control system, a power system, and a telemetry unit (figure 1). It is designed to carry a number of physical, optical and biological sensors, and can accommodate integration of additional sensors. The AMP is designed for deployment durations up to 90 days (depending on duty cycle and power system choice), and can travel 36 km vertically (ascent and descent) before it requiring servicing. The profiler is designed to maintain an upright attitude during profiling (< 10 degrees pitch and roll) and maintain a stable orientation with respect to the current direction. The key innovation of the AMP is its modular, compact, light-weight design that provides an unparalleled level of flexibility in sensing parameters, telemetry, and operational configuration in one self-contained platform.

The design and drive electronics of the AMP allow for a wide range of vertical profiling speeds to be achieved. By locating the core suite of bio-optical and physical instrumentation (sampling at intervals of 1 Hz or greater) near the top of the profiler, all measurements are obtained on a similar vertical plane. These two factors allow the AMP to obtain fine vertical scale resolution measurements with minimal perturbation of the sampled water column during the ascent profile. The design gives the AMP the capability to measure vertical features ranging from thin layers (10's of cm) to bulk water masses.

Two versions of the AMP profiler were developed, one targeted for inshore and near-coastal environments (< 50 m; termed the AMP-WQ50) configured with instrumentation designed for monitoring water quality applications, and one for coastal regions (< 100 m) capabilities of including a broader environmental sensing suite (termed AMP-ES100). While the overall size and weight of the

AMP varies depending on model, their shape (framing and flotation), instrumentation, and telemetry system, but their operation is nearly identical. The AMP platform is composed of 6 main components; 1) a supporting frame and rib structure and protective outer skin, 2) a buoyancy member, 3) an electronics bay, 4) a winch system, 5) an in situ sampling instrumentation suite, and 6) a power system. The AMP was designed as a symmetrical vertical hydrofoil, or rudder and a spar design in the horizontal dimension (figure 2). The center of mass and buoyancy are separated in the vertical dimension, providing a strong uprighting moment for the platform. These two features combined produce a stable profiling platform from which to conduct fine scale ($< 1\text{m}$) vertical resolution measurements. Additionally, the hydrofoil shape is such that the profiler will consistently orient itself with the leading edge pointing into the prevailing horizontal water current.



Figure 1. The AMP-ES100 profiler. Left panel shows a drawing of the profiler with the protective yellow skins, top cap and bottom battery footing installed. Middle panel shows a photograph of a profiler with one of the sides skins removed, exposing the center payload section (profiler show was delivered to NUWC, RI division). Right panel shows an AMP with both side panels removed. This profiler was used during the summer 2007 ONR OASIS experiment, and was deployed for ~2 weeks in September 2007 in 12 m off water near the Matha's Vineyard Coastal Observatory. The instrument configuration included a CTD (SBE49), a chlorophyll and backscattering sensor (WET Labs ECO FLNTUS), a single wavelength scattering sensor (WET Labs AUV-B), a current velocity sensor (Nortek Vector), and a hyperspectral absorption and attenuation meter (WET Labs ac-s).

The AMP structural components include an aluminum frame, a rear spar composed of High Density Polyethylene (HDPE), horizontal mounting plates made of HDPE, and an outer protective skin also made of HDPE (figure 2). A detachable aluminum footing attaches to the profiler frame using 4 bolts to provide a mounting structure for the profiler battery pack. Sheets of closed cell 1.5" thick hard PVC medium density foam cut to match the cross sectional shape of the AMP are used to provide flotation

(buoyancy) for the platform. The sheets can be easily removed or added should buoyancy adjustments be necessary. All of the flotation is located in the upper 1/3 portion of the profiler facilitating a separation the center of buoyancy and mass. The number of PVC sheets installed on the AMP can vary depending on the instrument configuration used on the platform. The target weight of the profiler in water is ~20 lbs positive buoyancy.

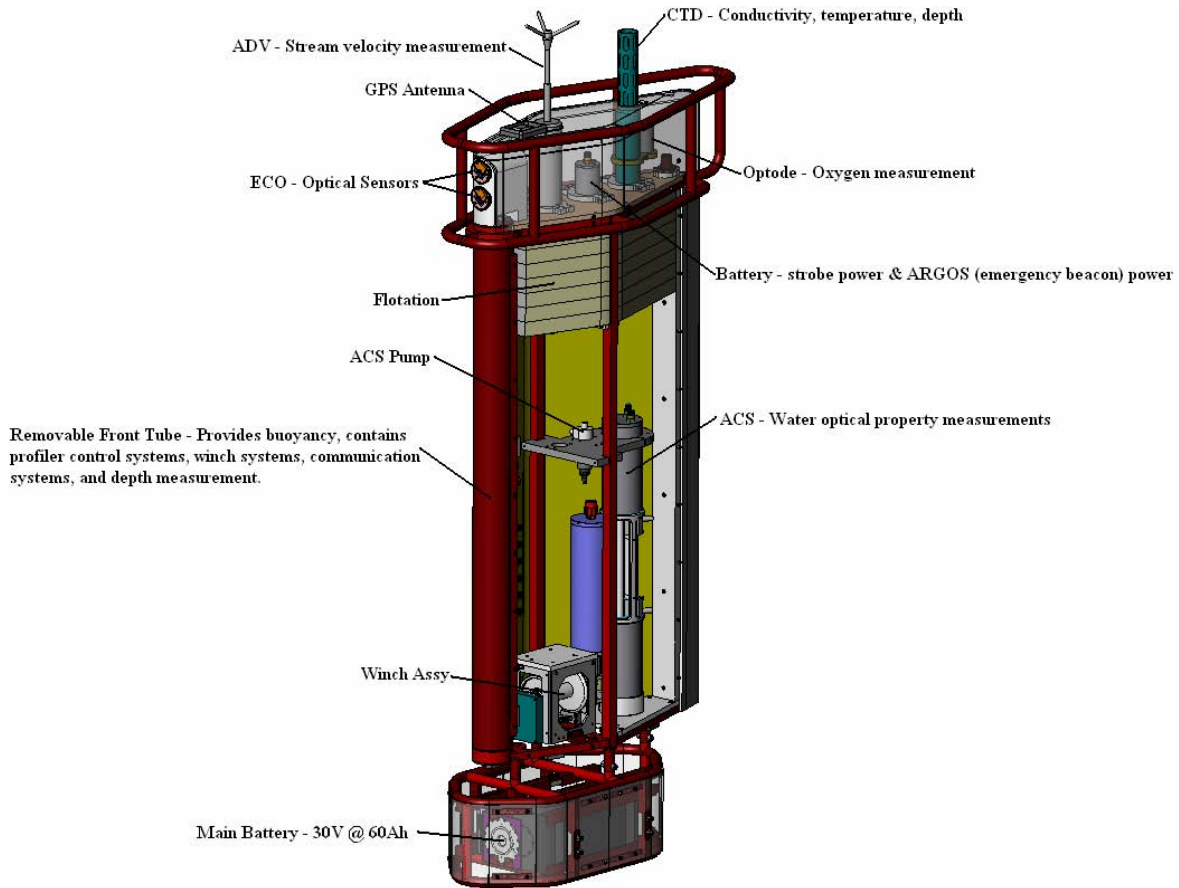


Figure 2 – Schematic of the Autonomous Moored Profiler (AMP-ES100) with one side skin panel removed, indicating the locations of the instruments, electronics bay, flotation, winch system, battery and other ancillary systems. Configuration of the platform is subject to change depending on instrument suite selected.

The core electronics of the AMP are located in a removable cylindrical pressure housing located vertically along the front axis of the profiler (figure 2). The primary control and power electronics for the AMP, winch system, winch motor control, telemetry system, and integrated GPS system are all located within this single pressure housing. Bulkhead connectors to connect to the instrumentation, winch system, telemetry system and power system are also located on this pressure housing. The primary package control electronics function is to provide power distribution, regulation and fault monitoring, instrument power and data acquisition, platform command and control, telemetry system interface and power control, winch system interface, and data storage and transfer. The package controller is, as the name implies, the main controller for the entire profiler. It has control relays that are used to supply power to all the other electronics within the profiler. The package controller handles

all incoming commands and outgoing messages to the host controller via the telemetry system. It is also responsible for the logging of all the instrument data during the ascent portion of a profile.

The primary function of the winch system electronics is to provide a command/control interface between the primary package controller and the winch motor. The winch controller is responsible for the control of the winch motor and for logging of the winch motor status, depth (pressure) and attitude (heading, tilt and roll). The winch controller is comprised of a servo motor controller, a digital compass with an integral tilt and roll sensor, a highly sensitive pressure sensor, and a microcontroller. Its primary responsibility is to interpret motion commands from the package controller and translate them into actual motion of the winch motor. It uses its integral pressure sensor to determine when depth travel limits have been reached. It also makes use of the position encoder within the winch motor to maintain precise knowledge of the position of the profiler along the rope. As a secondary task, the winch controller logs winch motor status, pressure, and attitude (heading, tilt and roll) as directed by the package controller. Information provided by these ancillary sensors is used by the package controller to determine platform ascent and descent speeds, vertical location of the platform in the water column, and for diagnostics in determining platform flight characteristics.

The winch motor consists of a custom NMEA-23 frame DC brushless servo motor, a 10 to 1 planetary gearhead and a ceramic face shaft seal (figure 3). The motor is IP67 rated (salt water wash down proof), such that the motor is able to operate if a leak into the motor housing should occur. It is coupled to the winch drum via a pair of bevel gears that allow the motor to be mounted at a right angle to the drum axis. The winch drum is the repository for the winch rope and is capable of holding as much as 250 m of .07” Plasma® rope. It also has an integral level wind that ensures that the rope pays in and out in a predictable manner (figure 3). To reduce wear on the winch rope, the level wind traveller and other fairleads are equipped with highly polished ceramic eyelets. A scalable gear box has also been designed to accommodate a broad range of profiling speeds.

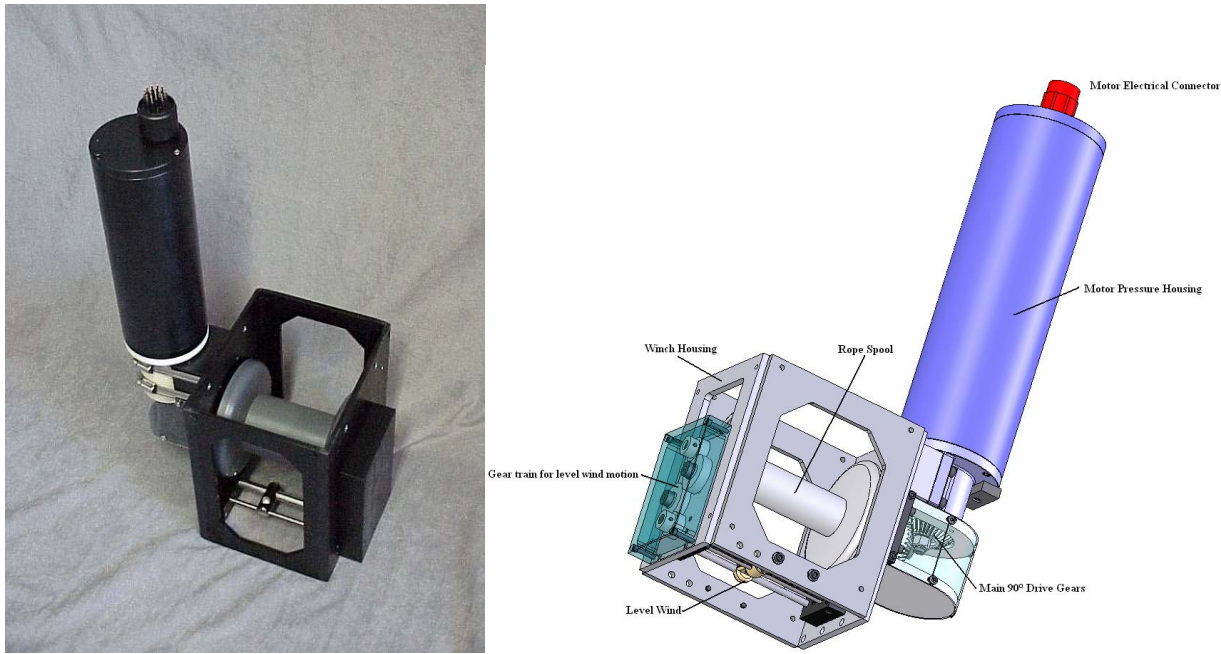


Figure 3. Picture and drawing of the winch system used on the AMP platform. Note the right angle worm gear drive, level wind and gearing, rope and rope spool. The winch drum is capable of holding 250 m of 0.07” Plasma® rope. The integral level wind ensures that the rope pays in and out in a predictable manner. To reduce wear on the winch rope, the level wind traveller and other fairleads are equipped with highly polished ceramic eyelets. A scalable gear box has also been designed to accommodate a broad range of profiling speeds.

The telemetry system acts simply as a reliable pipe for communications between the package controller and the host computer system. Due to the nature of wireless operation, the telemetry system will only operate when the antenna is above the surface of the water. The package controller will turn off the telemetry system except when the profiler is at the “radio depth”. It is important that the radio depth be shallow enough to allow the antenna to project out of the water. The AMP can accommodate several types of wireless telemetry systems including Freewave spread spectrum radio frequency, CDMA cellular and broadband cellular, and WiFi wireless technologies.

The science instrumentation suite included on an AMP profiler can vary depending on the desired measurement parameters to sample. A base suite of instrumentation consists of a conductivity, temperature and pressure (CTD, Sea-Bird Electronics SBE49) sensor, and a chlorophyll fluorescence and turbidity sensor (WET Labs FLNTUS). Many other sensors can be accommodated including dissolve oxygen (Sea-Bird Electronics SBE43 or Aanderaa oxygen optode), a current velocity sensor (Nortek Aquadopp or Vector), and other optical sensors (WET Labs ac-9, ac-s, FLCDS).

Currently, the AMP systems use Bluefin Robotics 1.5 kWh battery packs as the power plant to run the AMP. When fully charged, these packs will have a maximum voltage of 34V. Recharging of the packs is performed through a separate charger, requiring the battery to be disconnected from the profiler, but not necessarily removed from the profiler. The key advantages of the Bluefin battery pack are its compact size, high energy density (1.5 kWhr, 30 V nominal), built in power management controls, self containment (full ocean depth submersible, with pressure housing and cables), and is rechargeable.

The ascent and descent of the winch motor can be driven in one of 2 different modes, constant or variable drive modes. In constant motor velocity mode, the servo motor is commanded to operate by rotating the motor at a constant velocity (rpm). In this case, the winch is spooling rope off/on the drum at a constant rate. This control algorithm works well in quite waters, where no surface waves exist. However, in the presence of surface waves, strong time-varying pressure field is imparted on the water column, which acts to impart time varying accelerations/decelerations on the profiler's vertical movement in the water column. The winch motor can also operate in a variable velocity mode, whereby the rotational rate of the motor can vary over a profile extent. In this manner, the motor acts to maintain a constant tension on the profiling rope, such that when the profiler encounters a strong acceleration/deceleration force due to the surface waves (varying pressure field), the winch motor rotates faster/slower to maintain a constant tension on the profiling rope. The effects of the data quality and the profiler's ascent rate in the presence of surface waves when operating in constant velocity or constant current drive modes is shown in figure 4.

The profiler interface software is written in Java, thus providing for OS independence. The graphical interface is easy to use, and allows the user to seamlessly telemeter data and command and control sequencing (figure 5).

RESULTS

Results to date show that the hydrodynamic characteristics of the profiler design produce a stable orientation throughout the water column during ascent. Typically, the profiler exhibits less than 15 degrees pitch and roll, and maintains a constant heading, with the leading edge of the profiler pointed into the main current flow (figure 6). The flight characteristics are also relatively independent of profiling speed. The winch motor control algorithms have been extensively tested, and have been shown to produce highly effective in even in the presence of large surface gravity waves (~ 6 to 10 ft swell). The profiler motor drive and control electronics automatically adjust to the varying surface conditions, allowing for trouble-free profiling. During a recent field test (figure 4), the profiler was able to collect profiles error-free even in large surface wave conditions (swell ~9 ft, 8 second period).

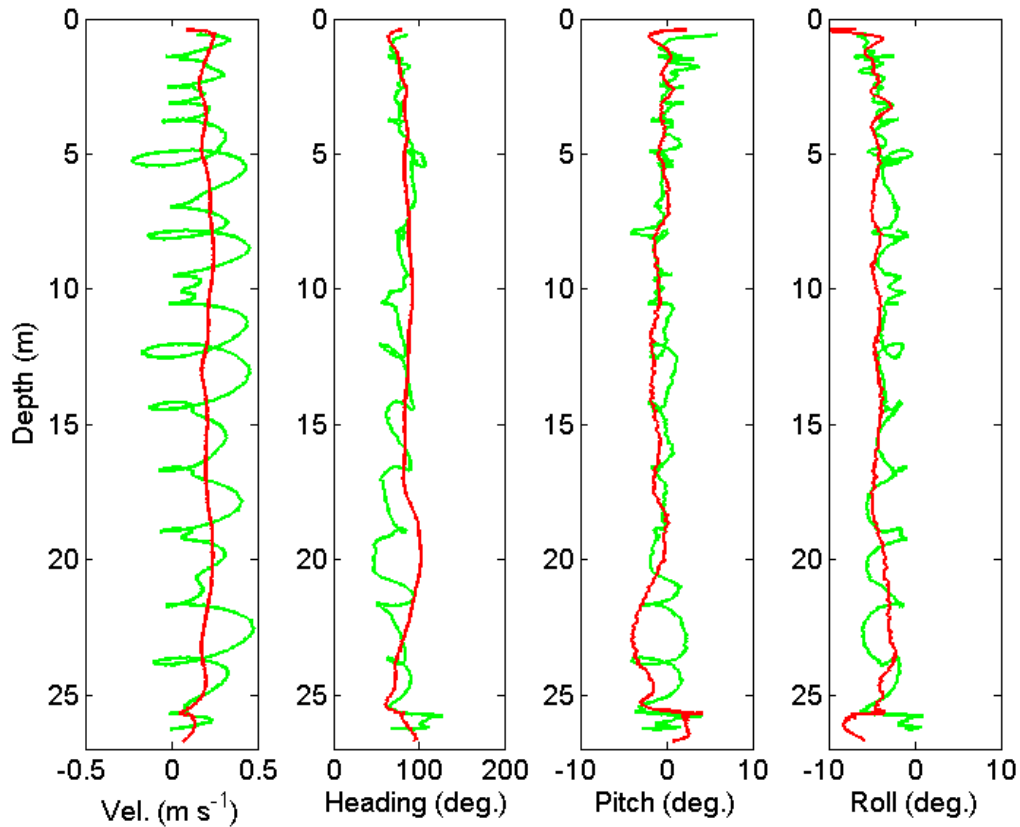


Figure 4. Consecutive profiles of a 28m water column made using an AMP profiler offshore of Newport, OR on 16 March 2007. Profiles were separated by 15 minutes. The winch was programmed to operate in two profiling modes, constant (green) mode and variable (red) mode. The ascent rate, profiler heading, pitch, and roll are plotted versus depth for each profile. Note the improved performance (contiguous ascent) using the variable control algorithm.

Several field demonstrations have been conducted to test and evaluate the AMP systems ability to reliably collect high resolution vertical data on the physical, optical, biological, and chemical properties of the ocean. At last count, over 45 field deployments have been conducted of 5 AMP profilers, spanning inshore and coastal waters. The WET Labs AMP-ES100 platform constructed under this contract was recently used during the ONR OASIS experiment conducted during September 2007 near the Martha's Vineyard Coastal Observatory. The AMP system provided hourly profiles of CTD, IOP's, chlorophyll and cDOM fluorescence, and currents over a 2 week period of the experiment (figure 7). The profiler was also used to test a new novel single wavelength scattering sensor (termed AUV-B) designed specifically for autonomous vehicles such as gliders and AUV's.

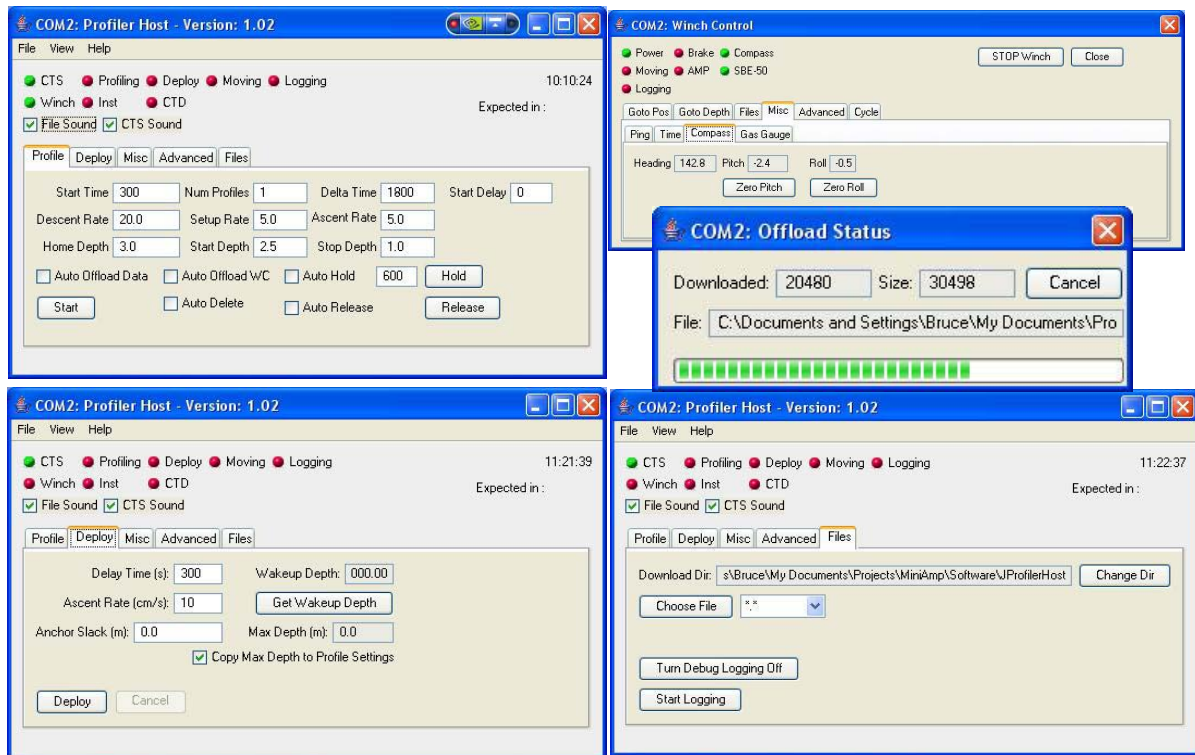


Figure 5. Screen captures of the AMP profiler host software program. Controls are provided for the profile start time, descent and ascent rates, bottom and surface stop depths, telemetry periods and file offloading. A separate module is also provided for deployment and recovery of the profiler. A post-telemetry file processing software module allows the user to seamlessly extract and merge science instrument data for visualization and analyses. All software is programmed in JAVA for platform independence.

In summary, our current development efforts have resulted in a hydrodynamically stable, power efficient, compact, modular profiling system that can routinely provide high vertical resolution measurements of physical, optical, and chemical data is easy to deploy and recover.

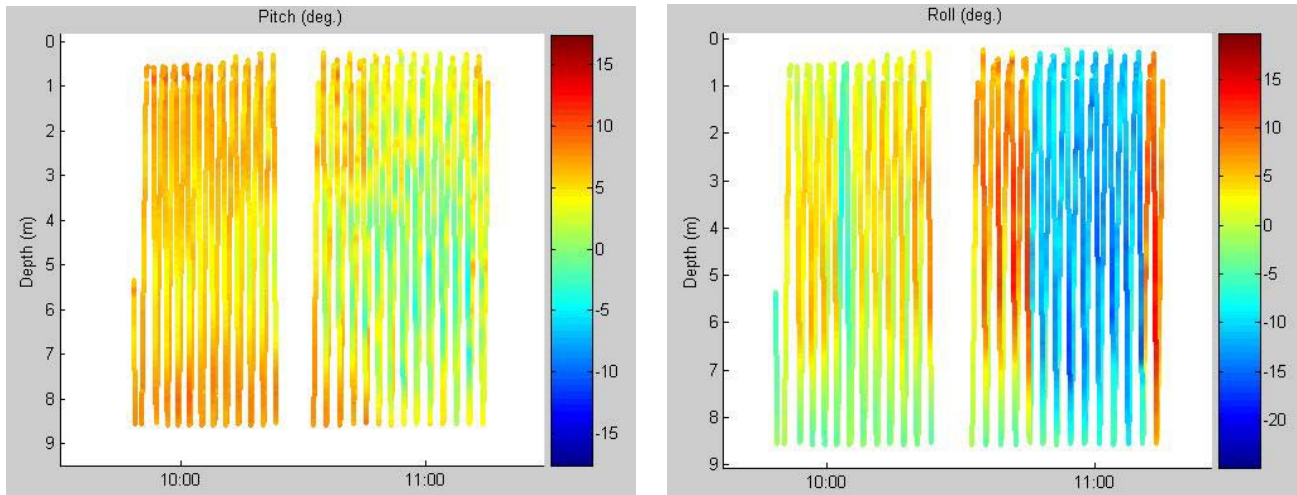


Figure 6. Time series plots of the AMP system pitch (left panel) and roll (right panel) collected on 4 May 2007 during a deployment in Yaquina Bay, OR. Note that the profiler was deployed during an ebb tidal cycle, where tidal currents were ~ 0.4 m/s within the Bay. Note that the profiler was relocated at approximately 10:20 (no data period).

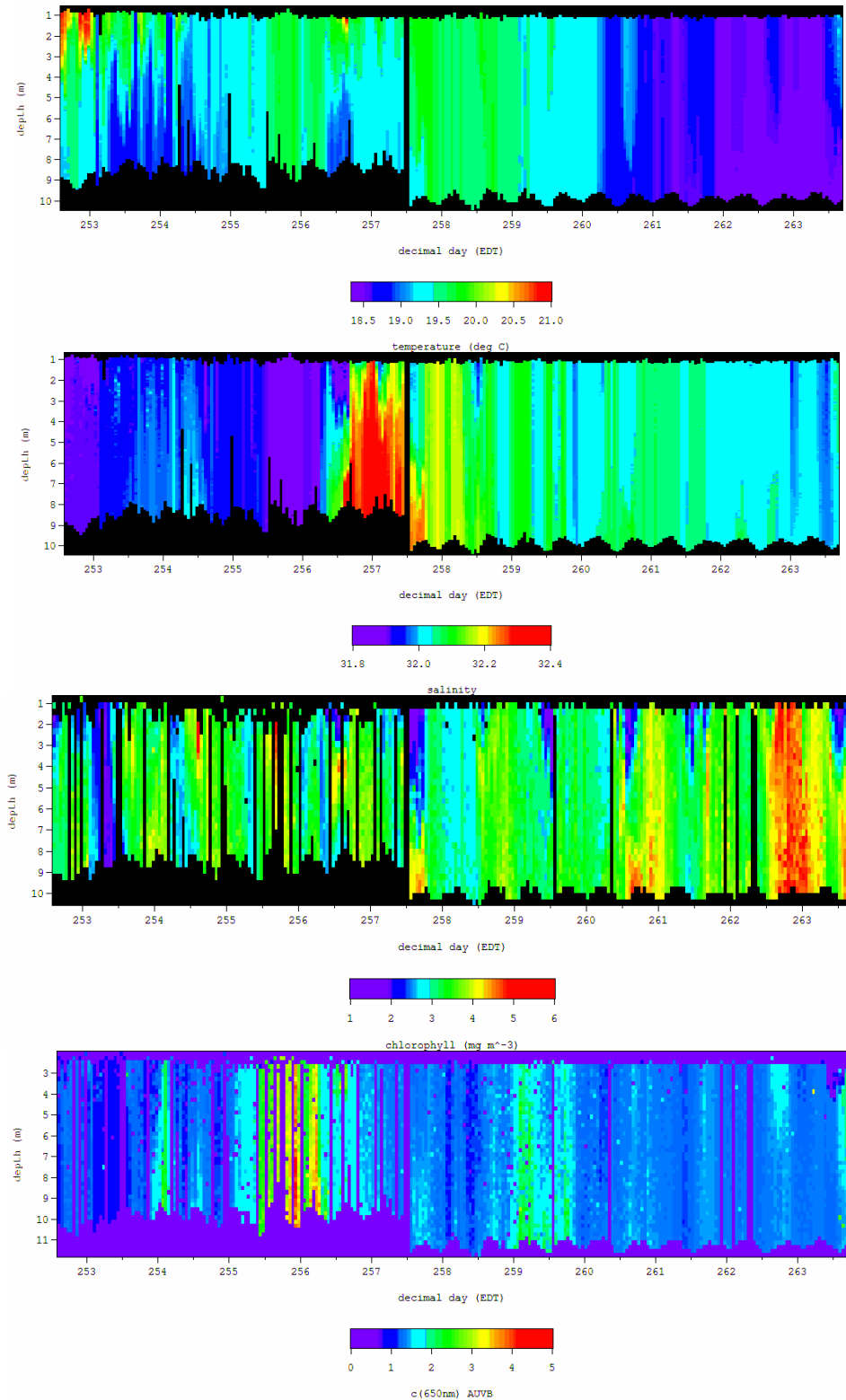


Figure 7. Time series of profile data collected using an AMP-ES100 profiler deployed in ~ 12m of water at the Martha's Vineyard Coastal Observatory during the ONR sponsored OASIS experiment in September 2007. Plots (top to bottom) show the hourly profiles of temperature, salinity, chlorophyll, and beam attenuation at 650nm. Note that on decimal day 257, the profiler was recovered for servicing (batteries) and redeployed.

IMPACT/APPLICATIONS

The AMP system will have immediate applicability for military operations requiring 4-D (space and time) knowledge of optical and physical properties within the battle space environment. These include optics-based mine and submarine countermeasures involving models of diver visibility, diver vulnerability, and radiative transfer, and lidar-based detection systems. Optical properties are also widely used by the non-military research community to determine a variety of water biogeochemical properties, including particle concentration, composition, and turbidity. The AMP is designed to meet the needs of applications demanding autonomous, long-term high vertical resolution profiles of physical and optical parameters from a platform that is small, robust, low maintenance, and hydrodynamic. Several regional scale ocean observing monitoring programs also require time series information on the vertical distributions of key water quality parameters to assimilate in predictive models. Many compact, cost-effective observation platforms are being sought after by the Navy and the ocean research and observing communities such as the NSF ORION and IOOS activities. Since there is currently no platform commercially available that fulfills all of these needs, there is a market vacuum for such a system. We believe that the innovations of the AMP system will fill a unique niche in ocean research that will service a broad spectrum of coastal oceanographic research, monitoring and military needs.

TRANSITIONS

There is a great demand for autonomous, moored profiling capabilities not only within the naval realm, but also in the science research, ocean observing and resource management communities. This has become clearly evident since initiation of our development activities of the AMP, as we have received numerous inquiries as to the status and potential availability of the AMP system. As one of the key goals of the project is to provide a profiling system that not only meets naval needs, but also to provide a turnkey solution to future and existing ocean observing and monitoring installations, we feel the involvement of these groups are crucial to insuring that the AMP system will meet a broad spectrum of user's needs.

Over the past year we have also received many of inquiries as to the current development status of the AMP system and the possible date for a commercial release. Inquires have come from not only the science research community, but also from federal, state and local management authorities. To this date, we have accumulated inquiries from over 20 different groups, which we have taken as a strong indication of the potential commercial market for the AMP system. In fact, over the past year we have provided several initial preliminary quotes for the AMP system to various researchers.

The NOAA Chesapeake Bay Office (NCBO) released a solicitation for the procurement of a continuous, real-time, shallow water, tethered profiling water quality and bio-optical property measurement system in 2005. This was a result of many conversations with Doug Wilson of the NCBO who became aware of our AMP development project through our web site. He expressed an interest in working with us to support the profiler development to meet the ecosystem resource management observing needs of the NCBO. As a result, we responded to the NOAA solicitation and were awarded the procurement to deliver a AMP prototype to the NCBO by the fall of 2006. An AMP-WQ50 system was delivered to NCBO in January of 2007, and was subsequently field tested in the Chesapeake Bay. Based on feedback from this field test with our NOAA customers, the AMP-WQ50 system was modified to improve the operational use of the AMP. In October 2007, the AMP-

WQ50 owned by NCBO is scheduled undergo several deployments in preparation for installation for operational use in Chesapeake Bay. We feel that this partnership with the NOAA NCBO has been invaluable in gaining operational experience and feedback from a potential AMP customer base and is helping to lead to an effective transition of this technology into the resource management and ocean observing arenas.

The winch system design for the AMP profiler has resulted in a stable, reliable, quantifiable product. In February of 2006, Drs. Percy Donaghay and Jim Sullivan requested that the winch systems used on their ORCAS profilers be replaced with the winch system currently designed for the AMP. As a result, Dr. Donaghay provided us with a purchase order to provide 5 new winch systems based on the AMP winch system design to upgrade their ORCAS profilers in preparation for the ONR LOCO experiment being conducted in July 2006. We delivered the 5 winch systems to Dr. Donaghay in June 2006, which were subsequently integrated onto their ORCAS systems. During the 2.5 week deployment of the profilers during the LOCO experiment, the ORCAS systems profiled nearly continuously, a dramatic improvement over the original winch systems used on the ORCAS profilers.

The Naval Underwater Warfare Center (NUWC) released a solicitation (N66604-06-Q-4166) for the procurement and development of a continuous, real-time, shallow water, autonomous profiling system with high frequency acoustic sampling capabilities. This was a result of many conversations with Ed Levine of NUWC who was aware of the ORCAS profiler's capabilities through interactions with our development partners at URI (Percy Donaghay and Jim Sullivan). WET Labs responded to the solicitation with a quote for the delivery of a single customized AMP (AMP-ES100) profiler that would include an additional acoustic data acquisition module and a high speed wireless telemetry system (CISCO wireless). WET Labs was awarded the contract on September 13, 2006. WET Labs partnered with SubChem systems to develop the custom AMP profiler for NUWC, with SubChem engineers providing the high-speed acoustic data acquisition system with a CISCO wireless telemetry system. An acceptance test deployment was successfully conducted in Narragansett Bay, RI by NUWC personnel and SubChem engineers, which completed the delivery.

One of the WET Labs AMP profilers constructed through this ONR SBIR was recently used in a Rhode Island Research Alliance project awarded to Dr. Al Hanson of SubChem Systems, Inc. The purpose of this project was to bring together research and industry to develop a real-time, interactive, 4-dimensional sampling array of in situ instrumentation called ORCASNET. The ORCASNET design included an AMP system (AMP-ES100), serving as the main sentinel sampling system for vertical biogeophysical measurements. A concept demonstration experiment was conducted in August of 2007 in Narragansett Bay, RI, during which time the profiler was deployed for a period of 3 days, providing hourly profiles which were telemetered to shore based data acquisition and database systems and posted to the web in near real time (< 10 minutes after profiler completion). In addition to the core instrumentation suite (CTD, FLNTUS), the AMP-ES100 platform also included a hyperspectral absorption and beam attenuation meter (WET Labs ac-s), two Sea-Bird Electronics dissolved oxygen sensors (SBE43), a Nortek Vector sensor, and a WET Labs single wavelength scattering sensor (AUV-B).

Thus, we feel that the AMP development supported by this ONR SBIR has already made significant headway into transitioning the technology into a commercial product. We feel the market for the AMP system has clearly been demonstrated, and that we have positioned our company to provide a viable commercial product for autonomous moored profiling needs in coastal to inshore waters. Although

much development still needs to be accomplished, we feel we are now at the stage where we have a solid prototype system from which the commercial product can become a reality.

RELATED PROJECTS

We have been working closely with Drs. Donaghay and Sullivan (University of Rhode Island) on the development of the AMP and to support their profiling systems (ORCAS) in the ONR LOCO project. This support has occurred hand in hand with the AMP development in order to take advantage of the past combined experience of both groups. WET Labs engineers provided substantial support to Drs. Donaghay and Sullivan deployment and operation of the ORCAS systems during the LOCO field experiments in 2005 and 2006 in Monterey Bay, CA.

In February of 2005, Drs. Jack Barth and Murray Levine of Oregon State University (OSU) was awarded an NSF grant through the Oceanographic Technology and Interdisciplinary Coordination program to develop in partnership with WET Labs a coastal autonomous profiling and boundary layer observing system. WET Labs role in this project (through a subcontract to OSU) was to develop a 250 m depth deployable autonomous moored profiler for the coastal environment, termed the X10 profiler, as well as an underwater docking and recharging system for the X10. This development is substantially different from the ONR supported AMP project. First, the X10 profiler have an extended depth range (250 m) and deployment range (6 months) than the AMP profiler (100 m, 3 months). Second, the instrumentation suite included in the X10 will accommodate a factor of 2 more sensors than the AMP. Third, the X10 power system will be recharged underwater when docked in a bottom anchor/monitoring platform (the AMP power system is completely self contained). Lastly, the mode of telemetry between the two systems is substantially different. A more detailed description of this project is given in *McLean and Barnard, 2005*. While there are substantial differences between the X10 and AMP, the core technology of a winch on board design is consistent between the two, and thus we have been leveraging much of the winch development.

Finally, the WET Labs AMP-ES100 platform constructed under this contract was recently used during the ONR OASIS experiment conducted during September 2007 near the Martha's Vineyard Coastal Observatory. The AMP system provided hourly profiles of CTD, IOP's, chlorophyll and cDOM fluorescence, and currents over a 2 week period of the experiment. The profiler was also used to test a new novel single wavelength scattering sensor (termed AUV-B) designed specifically for autonomous vehicles such as gliders and AUV's. The development of the AUV-B sensor is supported under an existing ONR Phase II SBIR to Dr. Michael Twardowski of WET Labs, and funding from this contract was leveraged to support integration of the AUV-B sensor with the AMP-ES100 platform and the 2 week deployment during the OASIS experiment.

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PUBLICATIONS

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